MECHANICAL AND MACHINABILITY BEHAVIOUR OF SHEEP WOOL FIBRE REINFORCED POLYESTER COMPOSITES

A SYNOPSIS

Submitted by

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(Reg. No. 201514265)

in partial fulfilment for the award of the degree

of

DOCTOR OF PHILOSOPHY

DEPARTMENT OF MECHANICAL ENGINEERING
SCHOOL OF MECHANICAL AERO AUTO AND CIVIL ENGINEERING
KALASALINGAM ACADEMY OF RESEARCH AND EDUCATION
(DEEMED TO BE UNIVERSITY)
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TAMIL NADU, INDIA
SEPTEMBER 2022

1. INTRODUCTION

A composite is a material which is produced from two or more constituent materials. These constituent materials have notably dissimilar chemical or physical properties and are merged to create a material whose properties are superior to those of the original components in a specific application. Composite materials are commonly classified as Organic Matrix Composites (OMC), Metal Matrix Composites (MMC) and Ceramic Matrix Composites (CMC). The term organic matrix composite is generally assumed to include two classes of composites, namely Polymer Matrix Composites (PMC) and carbon matrix composites commonly referred to as carbon-carbon composites. PMC are materials that uses organic polymer as matrix and fibre as reinforcement. There are different types of PMC according to the polymer types like thermoset and thermoplastic polymers. The types of thermosets for fibre reinforced composites include polyesters, epoxies and high performance thermosets, polyurethanes, silicon rubbers, phenol formaldehydes, unsaturated polyesters (UP). The types of thermoplastics include polyethylene (PE), polyvinyl chloride (PVC) and polystyrene (PS), which often are used for packaging. The reinforcing phase can either be fibrous or particulates in nature and if the fibres are derived from plants/other sources, they are called natural fibres. The environmental issues have resulted in considerable interest in the development of new composite materials with addition of more than one reinforcement that are biodegradable resources, such as natural fibres as low-cost and environment-friendly alternative for synthetic fibres. These fibres have been extracted by many process like mechanical decorticator, water retting, chemical retting etc. The fibres made from chemicals are called synthetic fibres and it may be glass, carbon, aramid, boron, ceramic fibres and etc. The fibres made from natural chemical (cellulose, hemicellulose, lignin, pectin, wax and moisture) are called natural fibres and it may be jute, flax, hemp, sisal, coir, banana, agave, snake grass fibre and etc. PMC materials offer certain advantages over metallic materials such as high strength-to-weight ratio, low thermal conductivity, damping, corrosion resistance, etc.

Due to their constitutional variability, anisotropy, and heat sensitivity, machining of Natural Fibre Reinforced Polymer Composite (NFRPC) is a somewhat tough process. Because of its unique features, the Abrasive Water Jet (AWJ) is preferred method for machining heterogeneous materials such as composite materials. Because it does not generate tool vibration, has no thermal distortion, imposes

minimum pressures on the work piece, and has great machining adaptability and flexibility, this approach is less susceptible to material qualities. There are various obstacles in AWJ cutting of heterogeneous composite materials. Problems such as delamination caused by the impact of the water jet, as well as time consumption when machining features like as slots and holes, necessitate more attention to the selection of process parameters. As a result, it is critical to create a technique for selecting process parameters for fibre reinforced composite materials. No machine manufacturer has yet provided an appropriate database for composite cutting, particularly for NFRPC.

This research discusses the effect of weight percentage (Wt%) of Sheep Wool Fibre Reinforced Polyester Composites (SWFRPC) on tensile, flexural, impact and hardness of the composites. The increase in Wt% of sheep wool fibre significantly increases tensile, flexural, impact and hardness. In addition to the mechanical properties, it also discusses the effect of abrasive water jet pressure, standoff distance, and traverse speed during machining of the SWFRPC. The surface roughness (R_a) and kerf angle (K_a) are considered as the output quality characteristics. The work uses compression moulding technique is used to fabricate SWFRPC and to study the effect of AWJ machining parameters on the R_a and K_a of the composites. The study aims to apply the Multiobjective Optimization by Ratio Analysis (MOORA) technique to optimize the AWJ machining parameters. It discusses the AWJ machining of SWFRPC to understand the influence and the effect of each parameter to identify optimal combination of AWJ machining parameters. The experiments are planned and conducted based on L_{27} orthogonal array. Abrasive Size (AS), Wt% of fibre (Wt%), Jet Pressure (P), Stand-off Distance (SOD), and Traverse Speed (TS) are considered as input parameters; R_a and K_a are considered as output parameters. MOORA is a tool employed to identify the best possible combination of AWJ machining parameters. The Support Vector Machine (SVM) algorithm is used in AWJ machining process and is compared to SVM hybrid models. The Differential Evolutionary (DE) algorithm and the entropy idea create a hybrid model. Further, the hybrid approach as SVM-Entropy; MOORA-SVM-Entropy is used to predicting and optimizing the AWJ machining parameters.

2. LITERATURE REVIEW

Polymer is one of the important materials in engineering application, due to the low density, ease of manufacturing at a low cost. Different types of polymers and their composites are developed to obtain good mechanical and physical properties. These composites are effective materials for industrial applications [1].

Composites fabricated from synthetic fibres possess excellent mechanical properties and they are relevant in both medium and high load applications, whereas NFRPC are considered good for low load bearing applications. The research community has made numerous successful attempts to utilise a variety of natural fibres, such as jute, banana, sisal, coir, kenaf, Palmyra and hemp for fabricating several bio-composites for low load carrying applications [2].

Composites have been fabricated by randomly placed coir fibre in polyester resin. From the results obtained, better flexural properties than the pure polyester were observed [3]. Similarly, the effect of fibre length on sisal fibre reinfoced polymer composites is studied and observed that the fibre loading concentration between the matrix and fibres possessed a better property with shorter fibres compared to longer fibres [4,5]. Arulmurugan and Venkateshwaran [6] observed that the effect of volume fraction of fibre on jute fibre with nanoclay filled hybrid polyester composites gave better mechanical strength at optimum volume fraction of 15 and 5 wt% of jute fibre and nanoclay.

Snake grass natural fibre reinfoced polymer composites of varying fibre length 10, 30, 60, 90, 120 and 150mm with different weight percentage of 10, 15, 20, 25 and 30% respectively is fabricated through compression moulding method. It was observed that the tensile strength of the composites is increased with increase in weight percentage of fibre and flexural strength of the composites is increased with increase in fibre length. And it is noted that the flexural strength is also increased by increase in weight percentage of reinforcement [7].

Waste rubber material has also been used as a reinforcement material for making polyester and epoxy resin composites. It was observed that an addition of waste rubber altered the density and thermal conductivity properties [8]. Rice straw fibre has also been used to reinforced with polyester resin. Both tensile and impact properties of the pure polyester resin and reinforced composites were tested. It was observed that addition of rice straw fibre provided 1.6 and 18 times better tensile and impact properties respectively [9].

Hybrid epoxy composites was prepared using jute-mat as reinforcement and nano coconut shell as filler with varying weight percentage of jute-mat (15, 30 and 45%) and nano coconut shell (5, 10, 15, 20 and 25%) and it was observed that the maximum tensile strength is obtained at 30 and 20 wt% of jute-mat and coconut shell powder and the flexural and impact strength of the composites is obtained at 30 and 25 wt% of jute-mat and coconut shell powder. Furthermore, contribution of the filler tends to decreases the strength due to improper distribution in the matrix material [10].

Animal fibres specifically contains proteins such as sheep wool, bird feathers and human hair. Furthermore, there are scarce attempts whereby animal fibres were used as reinforcement in NFRPC. To protect the environment from pollutions and to increase the value of fibre, animal fibre reinforced polymeric composites have been fabricated and studied [11]. For instance, animal fibre was used to produce composite materials for soundproof applications in buildings [12].

The non-traditional machining process is used for machining the newly developed composite materials is increasing day by day. Among the different sophisticated machining processes, the AWJ machining is attractive because of its ability to cut both hard and soft material without any thermal distortion or residual stress [13]. The merit of the AWJ machining machined surface is influenced by machining parameters, material properties and other environmental factors [14]. The R_a and K_a decide the value of the machined surface as the R_a decides the functional requirement and the life of the part, and the K_a describes the geometrical accuracy of the part being made [15].

The conventional machining process is also suitable for machining the composites. Still, the problem is the heterogeneous nature of the composite material, which leads to excessive tool wear, poor surface finish, and geometrical error. At the outset, during the machining process, the fibre part of the composite either delaminate or projects from the machined surface and leads to increased R_a [16]. The research community made a systematic study to understand the effects of machining parameters from hard to machine metal and heterogeneous materials like polymer, metal and ceramic-based composites [17].

The effects of machining on R_a and K_a of polymer-based composites are examined [17,18]. Kalirasu et al. [18] investigated the abrasive particle size has the greatest impact on the R_a and K_a of glass and coconut reinforced polyester composites. Patel and Shaikh [17] recommended that the traverse speed and standoff distance are

the major factors affecting the R_a and the K_a. Therefore, optimizations of these control variables are important to achieve the desired accuracy. As a result, R_a and K_a are the most important indicators in the AWJ machining process.

Various statistical methods are employed to identify the most beneficial combination of the machining factor using scientific methodologies. Investigators employed single objective, multiobjective, and soft computing algorithms to determine the best machining parameter combination. MOORA is the most successful way for tackling the multiobjective optimization issue among all other optimization tools. MOORA can be used in various ways to solve machining issues [19,20]. However, while the MOORA is a useful tool, it has two flaws. First, it's a type of discrete optimization method. The first flaw of the discrete optimization approach is its very high error rate because it is done exclusively on discrete samples.

Another example is when the weighting for output performance is incorrectly assigned when calculating the subtracted value, which results in a mistake in determining the optimal solution. The second problem may be solved using appropriate weight computation methods such as Principal Component Analysis (PCA), Entropy, and fuzzy, while the former can be solved using simple intelligence techniques. Nair and Kumanan [21] used weighted principal component evaluation with the pressure, standoff distance, traverse speed and abrasive volume as input parameters to assess the weight of the output performance characteristics.

Lu et al. [19] used the Grey Relational Analysis (GRA) – PCA approach to improve the high-end milling parameter. The PCA technique determines the weight to calculate the grey relationship coefficients. The PCA approach can forecast the precise weight for each performance criterion, and the best solution is found close to it. Rajesh et al. [22] used the GRA – Entropy technique to find the near-optimal solution for the turning parameter. The benefit of Entropy over PCA is that it is a straightforward approach. For example, the challenge of calculating the exact subtracted value can be solved using the method described above.

On the other hand, intelligent technology can powerfully identify and generalize to tackle ambiguity and nonlinear difficulties. For example, Mustafa et al. [23] considered the most influencing AWJ machining parameter to forecast the R_a of the machined part by the Artificial Neural Network (ANN) method. Zain et al. [24] employed ANN – Simulated Annealing (SA) to optimize the AWJ machining machining parameters to obtain better R_a and least K_a variation. To calculate the Grey

Relational Grade (GRG) of the ball-end milling process, Zhou et al. [20] used an Radial Basis Function Neural Network (RBFNN) model. In addition, the researcher attempted to solve the complexity and uncertainty problem by using ANN, Fuzzy, PCA, and Entropy based techniques to transform discrete into a continuous optimization problem. The challenge with neural network approaches is that they tend to generalize and over-fit models, lowering training accuracy. Therefore, many researchers attempt to adapt the discrete optimization process into a continuous one by combining statistical and soft computing technologies to reduce modelling error and computation time [25].

SVM is an intelligent tool for solving complicated problems with small sample size. In contrast, other intelligent methods, such as ANN, require a high sample size [26,27]. As a result, an algorithm must be developed to forecast and model the complex AWJ machining machining process using advanced techniques. One technique to save computing time during the training and testing phase is to reduce the number of input layers.

3. RESEARCH PROBLEM

Based on the literature review the following research gaps are identified,

- No systematic study is carried out to analyse the sheep wool fibre characteristics.
- Sheep wool fibre is not used as reinforcement in the thermoplastics and thermosets.
- The AWJ machining studies of SWFRPC is not explored
- Modelling of AWJ machining parameters for sheep wool reinforcement is not studied.

4. OBJECTIVE

- To characterise sheep wool fibre and explore the possibility uses as reinforcement material
- To study the mechanical properties of SWFRPC
- To investigate the machining performance of SWFRPC using mathematical tools.
- To develop the mathematical model for AWJ machining parameters.

5. ORGANIZATION OF THESIS

- **Chapter 1: Introduction**

This Chapter provides an overall view of the composite materials, its classifications, advantages, disadvantages, and applications. This chapter briefs about the discussion of polymer matrix composites with many types of natural fibres as reinforcement materials and few types of resins (polyester, epoxy, vinyl ester) used as a matrix material. The discussion also explains the animal fibre is used as reinforcement and polyester resin as matrix to prepare the composites. The mechanical testing of the composites and machining studies of composites using AWJ are also discussed.

- **Chapter 2: Literature Review**

This Chapter provides the information about the recent literature review on different types of natural fibres and its characteristics. The study extends to select a suitable fabrication technique, effect of fabrication conditions, process parameters and its influence on their mechanical properties. Further, this chapter discuss about the literature on AWJ machining, process parameters and its influence on output characteristics using hybrid mathematical tools for prediction and its importance. Based on the literature review, it presented the research gap in this area. The objectives of this research work are also presented.

- **Chapter 3: Materials and Experimental Details**

This chapter provides the research methodology used for this research work in Figure 1. The properties of matrix and reinforcement materials are explained in detail. The required number of composite plates were made by using compression moulding method with varying weight proportion of the materials. The equipment’s used for the characterization studies of Sheep Wool Fibre (SWF), mechanical testing, AWJ machining and to measure the quality characteristics of machined composites are discussed in detail.

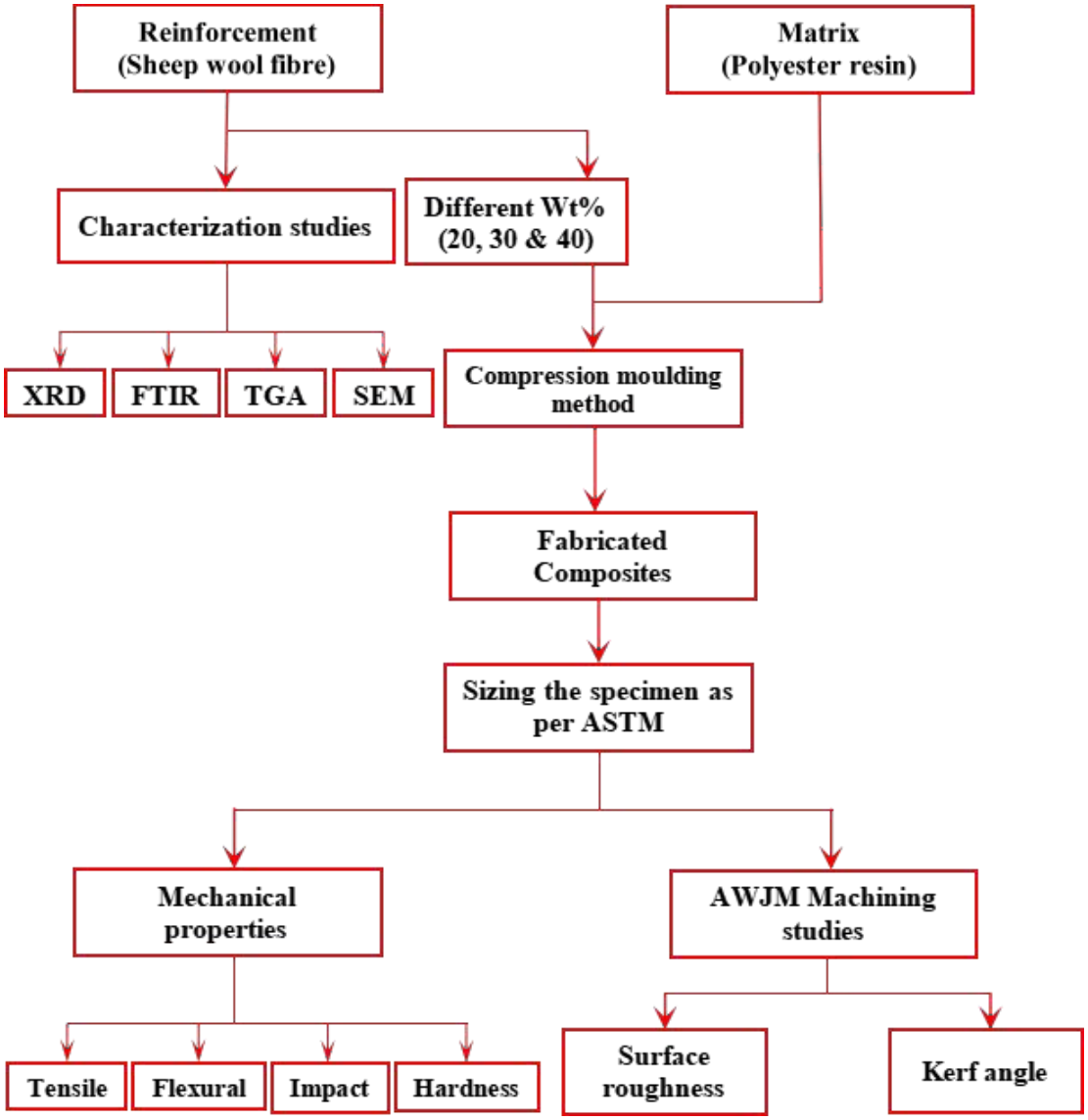

Figure 1 Research Methodology

- **Chapter 4: Characterization of SWF**

This chapter describes the characterization studies of sheep wool fibre using X-ray Diffraction (XRD), Fourier Transform-Infrared Spectroscopy (FTIR), Thermo-Gravimetric Analysis (TGA), R_a and Scanning Electron Microscope (SEM).

4.1 XRD

X-ray spectrum of the SWF was observed to understand the crystallinity nature of the SWF. The peaks in the spectrum of SWF were discussed in detail. The crystallinity of wool fibre plays an important role in its chemical, thermal, optical, and other physical properties. Moreover, the mechanical properties of fibre reinforced polymer composites are depends upon the crystallinity index value of fibre.

4.2 FTIR

FTIR test will give the presence of exact chemical structure of fibres. FTIR is used to gain insight into the presence and interactions of key components of fibres such as keratin, protein etc., The functional groups of chemical composition of the SWF were characterised, using FTIR analysis technique. Normally every animal fibres having keratin molecules, The presence of keratin structure molecules is confirmed on SWF by analysis of intensity and positions of amide bands.

4.3 TGA

TGA studies is used for determining a SWF thermal stability and its fraction of volatile components by monitoring the weight change that occurs as a sample is heated at a constant rate. The thermal stability of the SWF was analysed, using TGA.

4.4 Surface roughness

The roughness of SWF surfaces is important to the fibre-matrix interfacial bonding. It was observed that SWF possessed uneven surfaces on their outer layers. Rough fibre surfaces are mostly preferred during the fabrication of polymer composites, because they enhance mechanical bonding with polymer resin to the extent that the fibres will not easily pull out from the polymer matrix.

4.5 SEM

The surface topography of the SWF was examined, using SEM technique. It depicts that the fibre has an uneven surface with irregular scale boundaries. It was observed that the irregular surface texture of this fibre should provide a better interfacial adhesion than a smooth fibre with the matrix within a polymer composite system.

- **Chapter 5: Mechanical properties of SWFRPC**

This chapter describes the mechanical properties of sheep wool fibre reinforced polyester composites is presented in detail.

5.1 Tensile test

The tensile test for the randomly oriented SWFRPC was done in accordance with ASTM D3039 standard, using a universal testing machine. The tensile test of rectangular samples with dimension of 200X20X3mm were cut from the composite plates, using a reciprocating blade cutter. The SWFRPC of three different fibre contents of 20, 30 and 40 wt% were tested. In each wt% composition, five identical samples were selected to carry out the test and the average value was recorded.

5.2 Flexural test

The flexural responses of all the SWFRPC samples with varied fibre loadings were obtained according to the ASTM D790 standard. The dimension of the samples was 127X13X3mm. The flexural test was conducted on a universal testing machine, using three-point bending method. In each wt% composition, five identical samples were selected to carry out the test and the average value was recorded.

5.3 Impact test

Impact test of an un-notched composite samples with a dimension of 65X13X3mm was performed according to the ASTM D256 standard. All the SWFRPC with different fibre loadings were tested. In each wt% composition, five identical samples were selected to carry out the test and the average value was obtained.

5.4 Hardness test

Hardness of the composite was measured as per ASTM D-2240 using Shore D hardness tester. Hardness measuring instrumentation employing a sharp needle that was intended directly onto the surface of sample to determine the hardness. Information was found over five completely different positions. Information revealed during this work are computed as averages of the activity performed for five samples.

- **Chapter 6: Machining studies of SWFRPC**

This chapter deals with AWJ machining studies of SWFRPC, which includes experimental runs and its responses. This study extends to different cutting parameters and its level settings and to measure the output performance as R_a and K_a. Further, this chapter explains the detailed procedure of multi objective optimization method to perform AWJ machining studies along with mathematical tools used for performing multi objective optimization as MOORA technique is discussed in detail.

- **Chapter 7: Modelling and prediction approach on the surface qualities of SWFRPC**

This chapter describes modelling and prediction approach on the surface qualities of SWFRPC. This chapter extends study on hybrid algorithms effectiveness in predicting and optimizing the AWJ machining parameters. The SVM algorithm represents the AWJ machining process and is compared to SVM hybrid models in Figure 2. The DE algorithm and the Entropy idea create a hybrid model. Further, this chapter explains the hybrid approach as SVM-Entropy; MOORA-SVM-Entropy is discussed in detail.

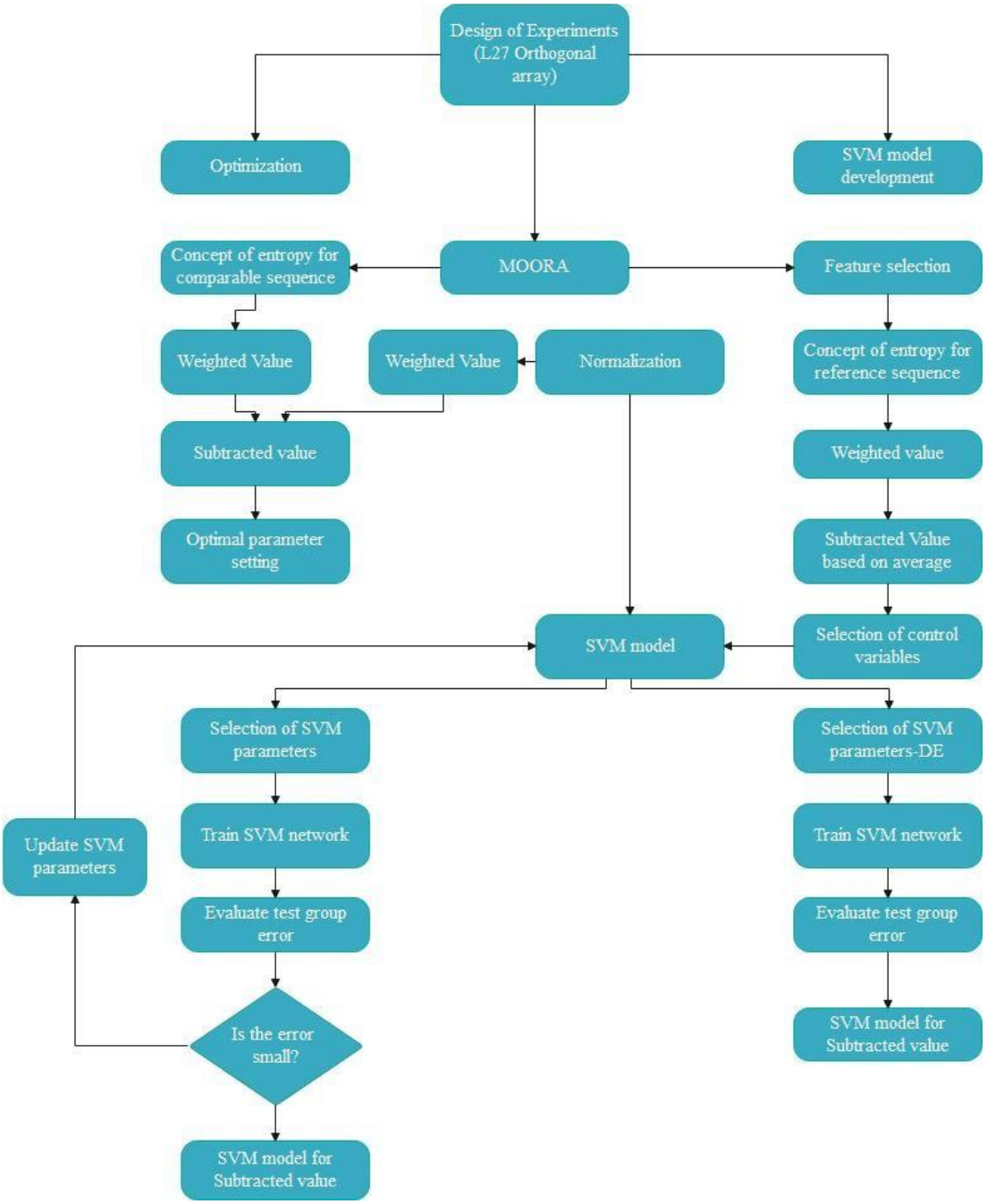

Figure 2 Proposed methodology for Hybrid SVM

- **Chapter 8: Conclusion**

➢ Based on the characterisation studies XRD, FTIR, TGA and R_a of SWF provides better properties of the composite happen with improved crystallization rate and thermal stability due to presence of keratin and better fibre-matrix interfacial adhesion and mechanical interlocking are promoted.

➢ Based on the mechanical properties tensile, flexural, impact and hardness strength of SWFRPC, it was apparent that the optimum mechanical properties were obtained with 40 wt% SWFRPC sample, due to a better fibre-matrix interfacial

adhesion, as confirmed from its micrographs. However, the SEM images of the fractured samples depicted that the fabricated SWFRPC samples possessed some voids.

- The classic MOORA and MOORA-Entropy hybrid approaches to AWJ machining parameter optimization. The optimal parameter settings for both procedures are compared, and it is discovered that for the first four ranks, the optimal parameter values are the same, then it changes. The optimal machining conditions are TS 30mm/min, P 120MPa, SOD 0.5mm, Wt% 40, and AS 80μm.
- MOORA can be used to choose features as well. The ranking for both the method and the entropy method is experimentally the same. Even so, the MOORA levels differ from one experiment to the next. Both systems' most influential control variables are AS, P, TS, Wt% and SOD.
- The DE and Entropy principles increase the model's performance by 21.6 percent compared to the traditional SVM approach. The performance of the feature selection approach on the SVM model is also studied. The number of layers with two control variables enhances performance by 38.7% compared to the standard method.

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7. LIST OF PUBLICATIONS

1. **J. Manivannan**, S. Rajesh, K. Mayandi, N. Rajini, S.O. Ismail, F. Mohammad, M.K. Kuzman and H.A. Al-Lohedan, Animal fibre characterization and fibre loading effect on mechanical behaviors of sheep wool fibre reinforced polyester composites, *Journal of Natural fibres*, (2020), DOI: 10.1080/15440478.2020.1848743. **(Impact Factor – 5.323)**
2. **J. Manivannan**, S. Rajesh, K. Mayandi and M.T.H. Sultan, Tensile and Hardness Properties of Sheep Wool fibre Reinforced Polyester Composite, *Materials Science Forum*, **969** (2019), 266-270. **(Scopus)**
3. **J. Manivannan**, S. Rajesh, K. Mayandi, S. Syath Abuthakeer, M. Ravichandran, T. Senthil Muthu Kumar, M.R. Sanjay and Suchart Siengchin, A novel and prediction approach of sheep wool reinforced polyester composites: Surface qualities and hybrid modeling, *Polymer Composites*, **43** (8) (2022), 5274-5290. **(Impact Factor – 3.171)**